Sonoelectronics

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DARPA is embarking upon a new research and development program called Sonoelectronics, a comprehensive three-year technology thrust aimed at creating new capability for ultrasonic imaging under water. The baseline imager architecture is a two-dimensional array of ultrasonic transducers, each coupled with high-precision readout electronics. The technical strategy in developing the imager is sonoelectronic integration, whereby surface and bulk micromachining techniques are used to produce the transducer arrays and acoustic coupling structures in silicon substrates, and the readout electronics is fabricated with a high-density, low-cost Si CMOS process.

Outline

- DoD critical need
  - Underwater imaging of sea mines
- Acoustic imaging fundamentals
- Sonoelectronics baseline technology
- Technology focus areas
  - Transducers and acoustic amplifiers
  - Electronic read-out and acoustic matching structures
  - Illumination technology
- Future capabilities

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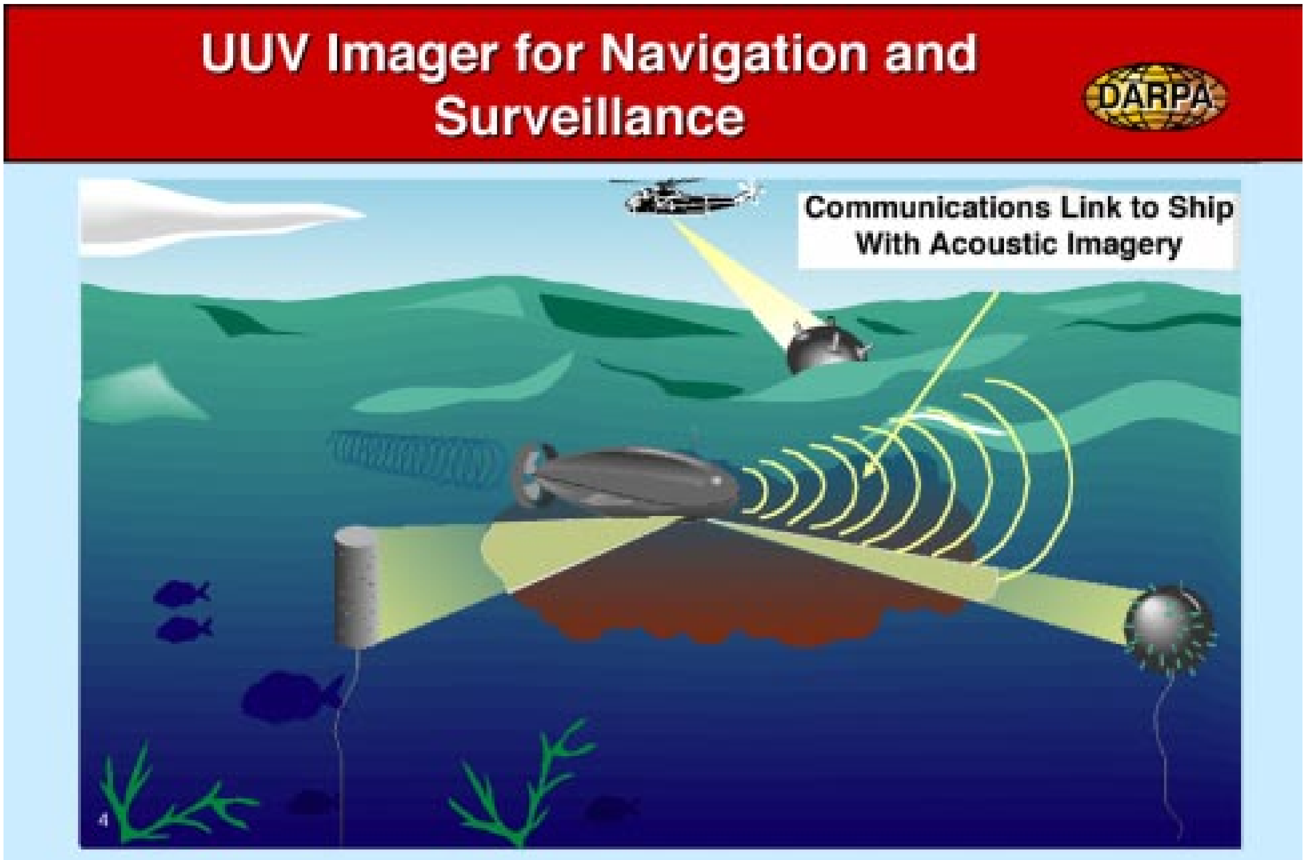
The presentation begins by stating the critical DoD need for high-resolution acoustic imaging of sea mines. It then reviews the physics and phenomenology of ultrasonic propagation and imaging under water. Following this review, it introduces the baseline Sonoelectronics technology, and then addresses the technology focus areas in some detail. This includes ultrasonic transducers and acoustic amplifiers, electronic read-out and acoustic matching structures, and ultrasonic illumination technology. Finally, the presentation offers a look at other possible applications of the basic Sonoelectronics technology, such as ultrasonic focusing and adaptive beam forming for non-invasive surgery.

A compelling DoD application is the acoustical imaging of sea mines. Since World War I, these have evolved from rather simple bottom-moored direct-contact surface mines to sub-surface or buried mines with proximity triggering. The latter class of mines are readily deployed in littoral waters or surf zones, which tend to be turbid and highly cluttered. This impedes the task of detection and identification of the mines because the identification is presently carried out using either optical techniques from airborne platforms or human vision. The ability to acoustically image through turbid and cluttered water could greatly improve the probability of detection and identification, reduce the time for neutralization, and mitigate accidental triggering.



A second application for sonoelectronic imaging arrays is on unmanned underwater vehicles (UUVs). Because of the greater aperture allowed by this platform (up to ~40 cm), higher resolution can be obtained than in the diver-held application if the operational frequency remains above 1 MHz. However, the UUV will not likely be useful at the close ranges practiced by divers, so that the operational frequency will have to be lower to deal with the high attenuation. Fortunately, this can be done without significant loss of resolution by fully populating the aperture with a sonoelectronic array. The UUV also provides the capability for remote surveillance of mines and other underwater objects by a diver or other operator on a surface platform. In this case, the acoustic imagery could be transmitted between the UUV and the human observer by an underwater acoustic communication link.

A Grand Technical Challenge

DARPA

Develop Acoustic Imagers Having Properties Similar to Video Cameras:

- Real-time imaging (~ 30 frames/second)
- Good imaging in cluttered environments
- Compact, low power consumption (battery operated)
- Stealthy (difficult to detect by other acoustic sensors)

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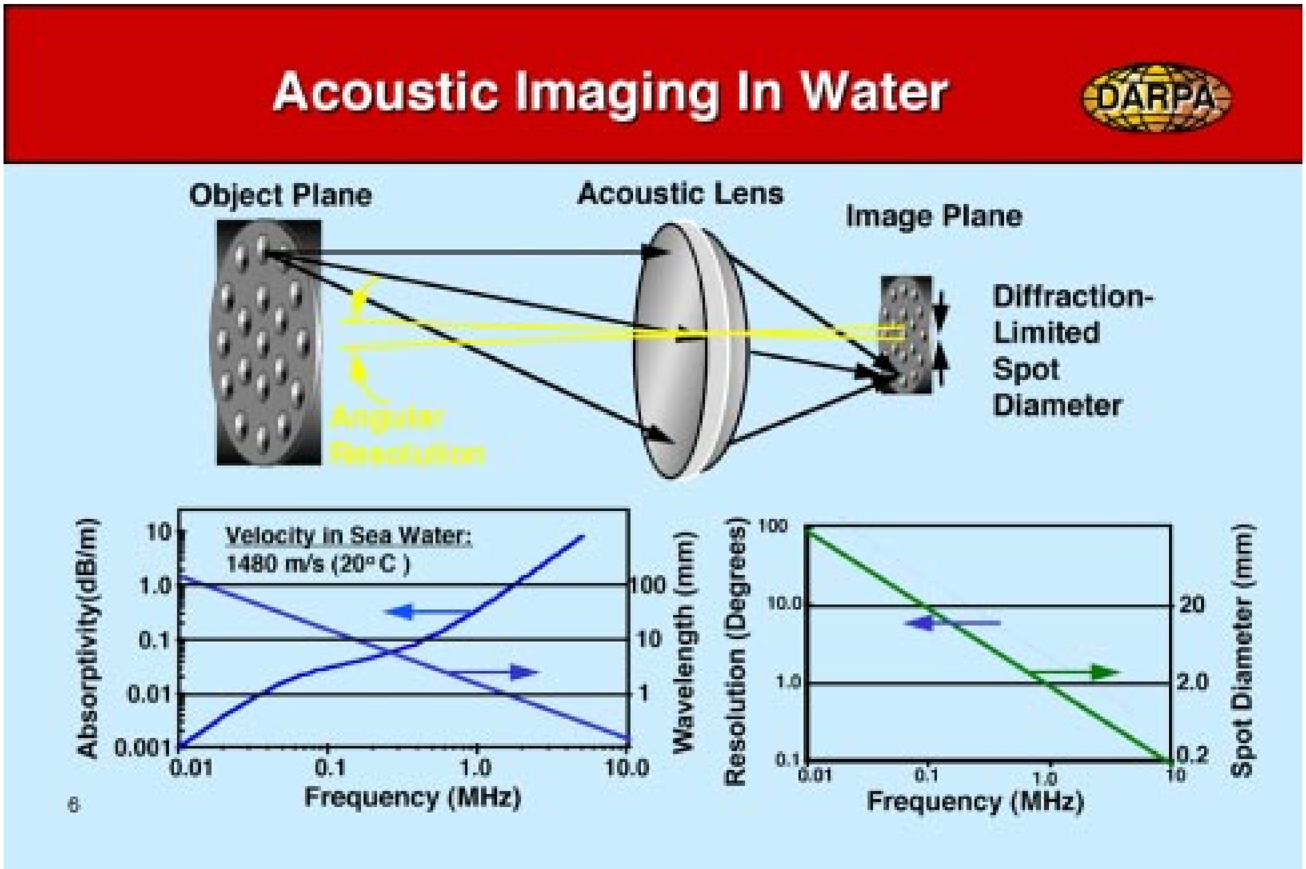
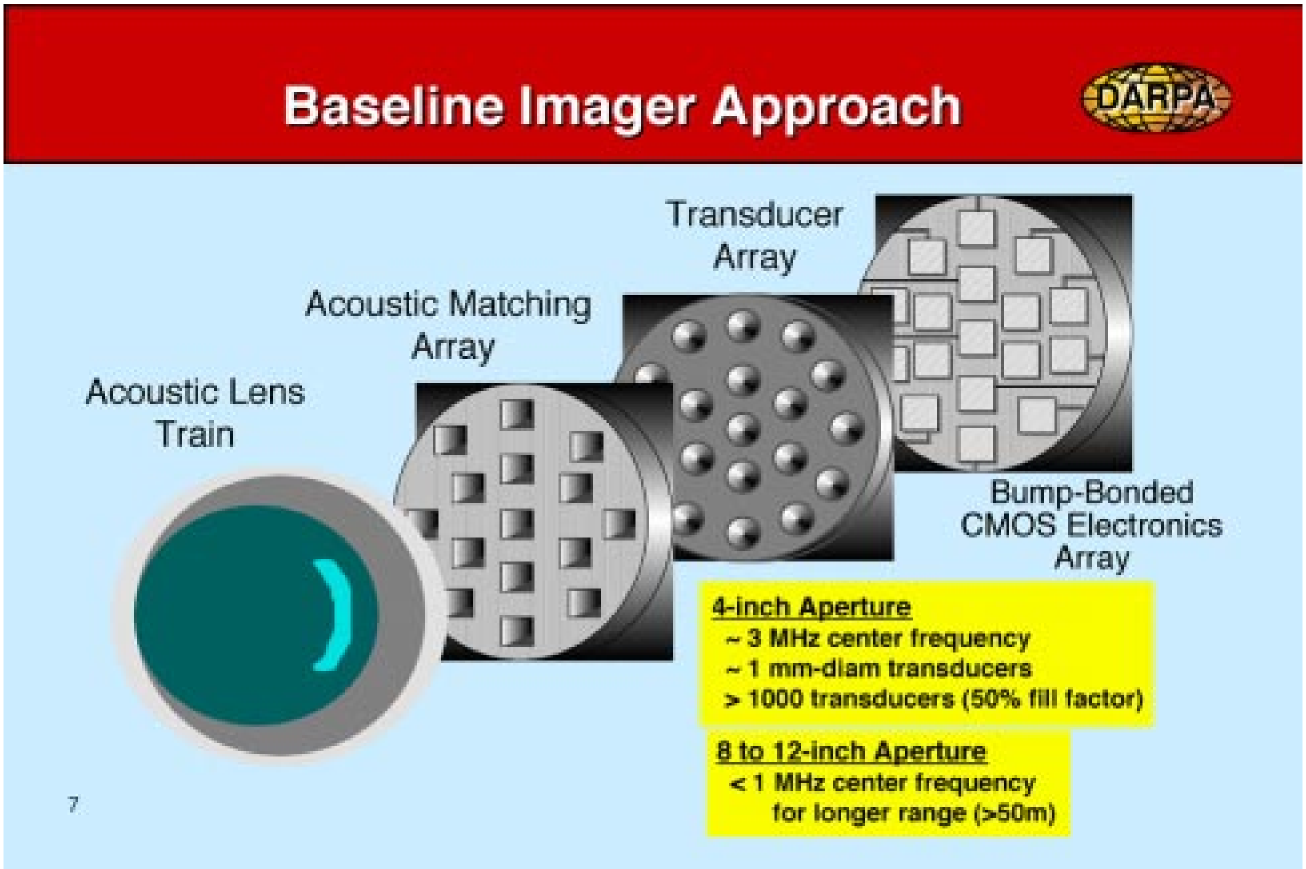
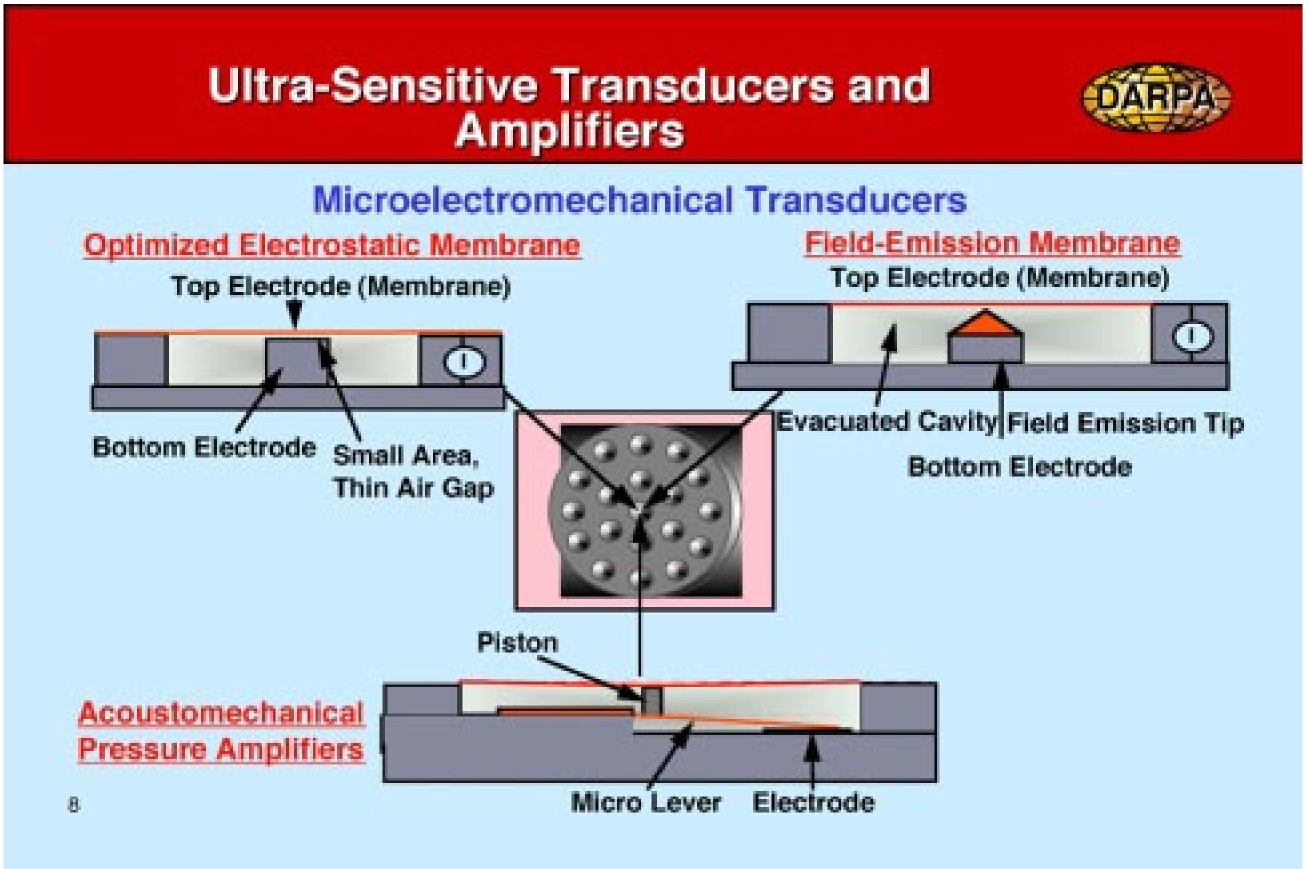
In the Sonoelectronics program, the baseline approach is motivated by the superior operational characteristics of modern visible and infrared imagers, such as real-time imaging at approximately 30 frames per second, high contrast and spatial resolution in cluttered environments, human portability, and operability over long periods of time with low power consumption. Another desirable characteristic is that the sonoelectronic imager be stealthy with respect to other acoustic sensors to prevent accidental triggering of mines and to avoid detection by the enemy.



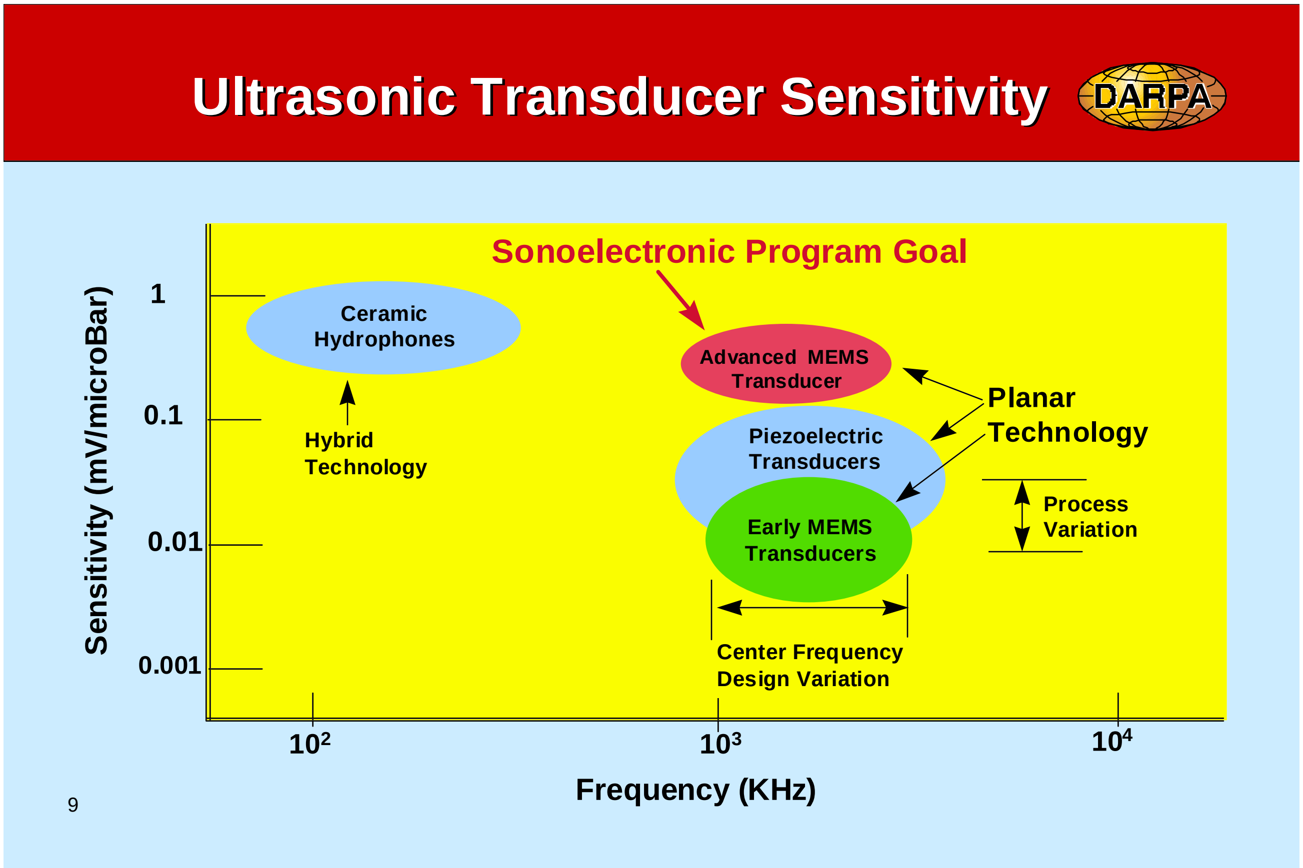
The physical basis for underwater acoustic imaging is analogous to the imaging in geometrical optics. Images can be formed by using an acoustic lens, or its electronic equivalent, and transferring the acoustic radiation from an object plane into an image plane. The fidelity of this process depends on the degree to which acoustic radiation from a given point in the object plane maps uniquely to a corresponding point in the image plane. Among other factors, diffraction can distort the image quality when the ratio of the diameter of the lens to the acoustic wavelength is not very large. To reduce the effect of diffraction, the baseband frequency in the Sonoelectronics program is above 1 MHz where the acoustic wavelength in water falls below 1 mm. In this range, typical acoustic lens characteristics (e.g., f/# = 1.5) will yield resolution angles less than 1 degree and spot diameters in the image plane less than 1 mm. With such performance, the image can be formed using a two-dimensional array of transducers that convert the acoustic pressure in the image plane to electrical signals. One problem with this approach is the rather strong absorption of acoustic radiation in water at frequencies above ~1 MHz. This establishes an engineering tradeoff for the imager design. Lower frequency operation has low attenuation and, hence, allows relatively weak illumination power. Higher frequency operation favors better spatial resolution per unit imager area but requires greater illumination power to overcome the attenuation.



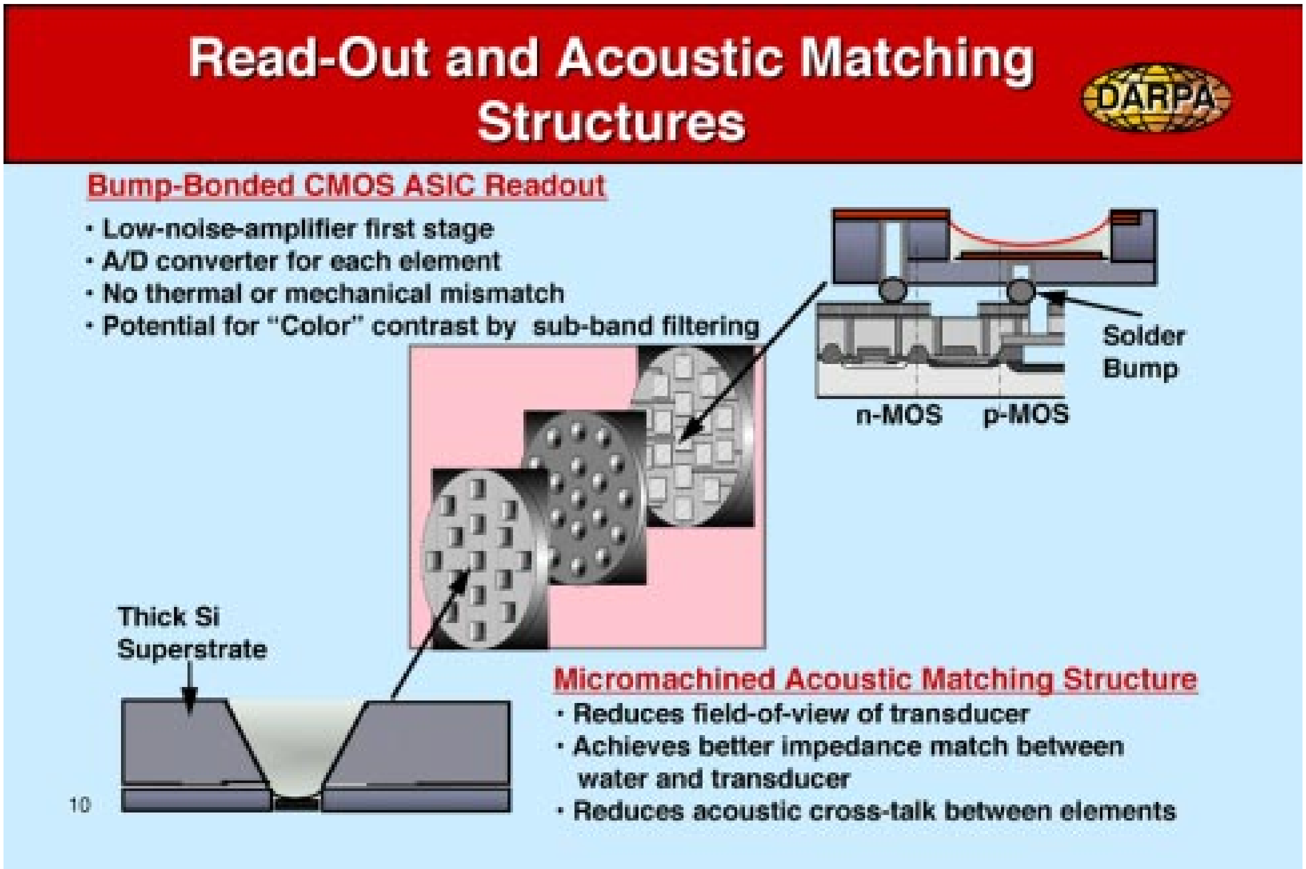
This chart shows a perspective view of one possible means of sonoelectronic integration. In this case, the tasks of acoustic focusing, matching, transduction, and electronic read-out are carried out by four separate components, all low cost, lightweight and readily integrable with one another. The matching, transduction, and read-out functions are all fabricated in silicon to take advantage of recent advances in surface and bulk micromachining, and low-cost VLSI with standard CMOS processes. Although a candidate acoustic lens is based simply on composite plastic materials, it is also possible to eliminate the lens and develop images by electronic beam forming. Such beam forming has proven difficult in the analogous field of electromagnetic (e.g., radar) imaging, but the acoustic problem is expected to be much simpler because of the lower operational frequencies.



Acoustic transducers are being investigated that offer unprecedented levels of sensitivity and bandwidth. A candidate device is the MEMS diaphragm in which acoustic power is converted into an electronic signal via a thin membrane coupled with a planar electrode or with a field-emission tip. In the former case, the transducer membrane acts as a variable capacitor, and in the latter case as a variable resistor. Also of interest are compound micromechanical, microfluidic, or other structures capable of amplifying the acoustic pressure or velocity, or both. In this way, acoustic power amplification can occur, which will reduce the effect of noise in the following stage of electronics.

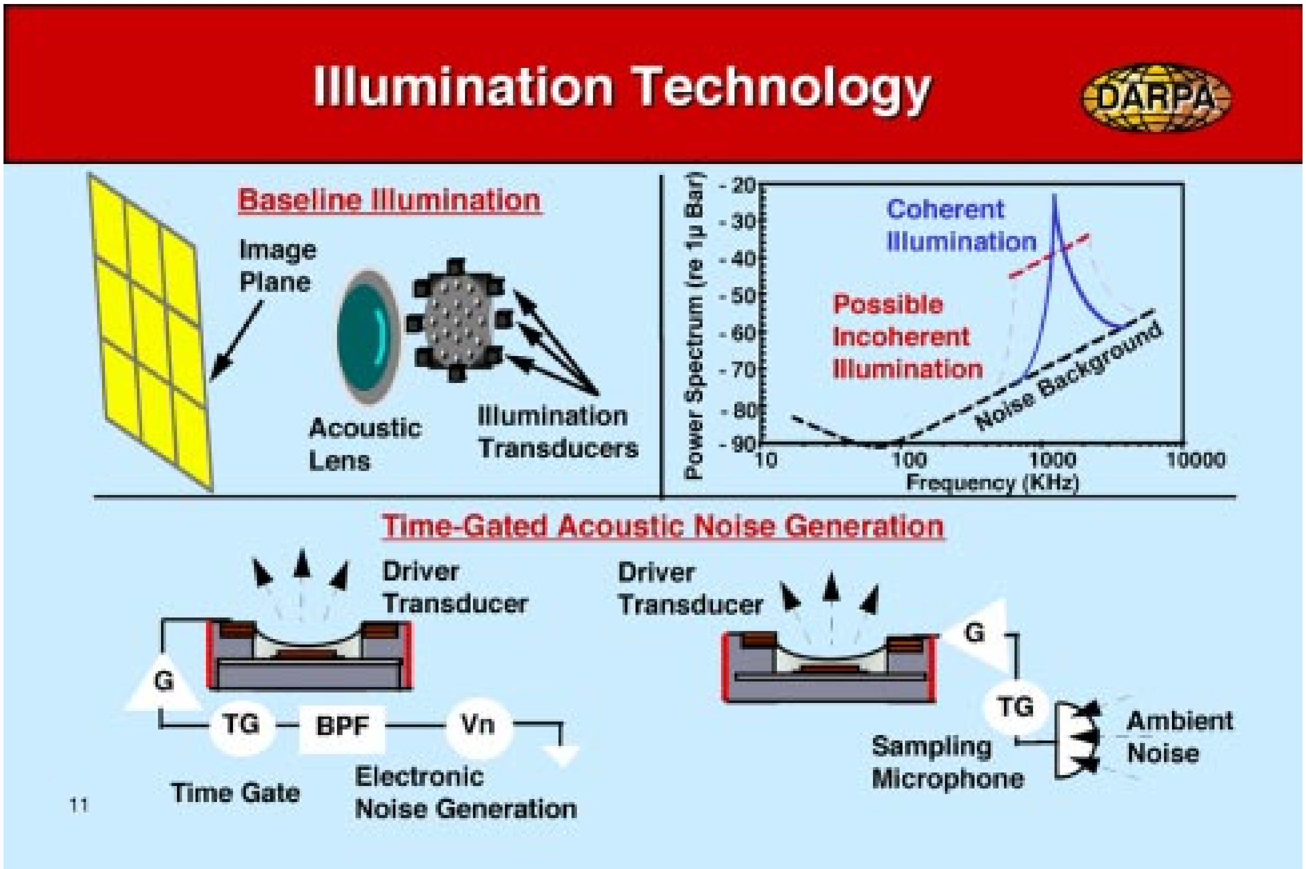


This graph acts as a useful technology road map for the acoustic transducers or amplifiers being developed in the Sonoelectronics program. The axes are acoustic sensitivity vs. frequency, the state-of-the-art being defined by ceramic cylindrical hydrophones at frequencies below approximately 1 MHz and by thin-film piezoelectric transducers above 1 MHz. The sensitivity of the acoustic amplifiers and, perhaps, the transducers is expected to rise above the piezoelectric transducers over the course of the program. However, it is expected that the instantaneous bandwidth will be somewhat inferior being that piezoelectric transducers are inherently matched to the high acoustic impedance of water over a large bandwidth without transformers.

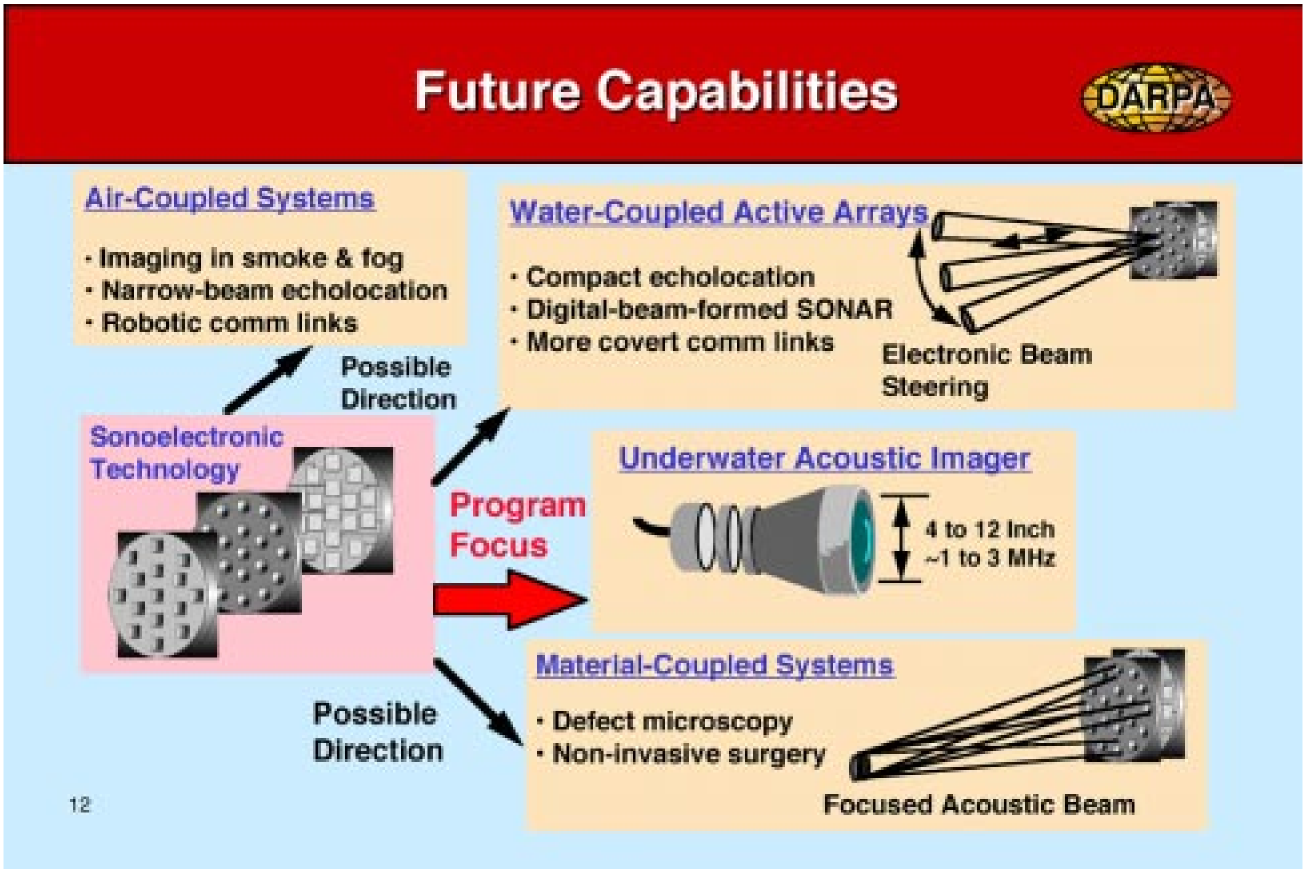


A difficulty that novel acoustic transducers or amplifiers face is mechanical impedance mismatch to the water medium. To help alleviate this mismatch and create a superior imaging front end, acoustic coupling and transformer structures will be addressed. One promising approach is bulk micromachined acoustic feedhorns, such as those shown in the lower left portion of the chart.

Also of importance in the acoustic imager is the layout and performance of the electronic read-out circuit. Three key functions are desired from this circuit: (1) low-noise buffer amplification to interface with the acoustic transducers and amplifiers, (2) analog-to-digital conversion in each pixel, and (3) digital multiplexing to transfer the electronic signals corresponding to acoustic images off chip. It is desirable to have all these functions carried out by a standard Si CMOS technology on a separate substrate that bonds easily and robustly to the imager array.



A challenging issue in developing underwater imaging capability is acoustic illumination. At higher ultrasonic frequencies where the wavelength is short enough to consider a hand-held imager, the attenuation is high enough to make background illumination of objects weak. Therefore, artificial illumination techniques are being considered, such as acoustic generation from the imager itself. The radiation might be coherent, quasi-coherent, or incoherent, but will be applied with image quality in mind. For example, it is desirable to eliminate the problems of glint and speckle of coherently illuminated (e.g., side-scanned sonar) systems.



Although concentrated on the immediate DoD need of imaging mines, the Sonoelectronics technology lends itself to other possible underwater, air-coupled, and material-coupled applications. Many of these applications center around the inherent ability of sonoelectronic transducer arrays to generate electronically steerable beams. For example, a sonoelectronic array could act as the transmit antenna in an underwater communications link capable of pointing and tracking with much greater accuracy and speed than conventional horn- or lens-based acoustic antennas. Similarly, a large area sonoelectronic array could act as a highly directed audible microphone capable of selective eavesdropping at a distance in noisy and crowded environments. Finally, a high-intensity sonoelectronics transmit array operating at comparable frequencies to the underwater imager would be a key component of a system capable of various non-invasive medical procedures, such as precise lithotripsy (disintegration of gall and kidney stones) and angioplasty (removal of vascular plaque).